



Holocene temperature, humidity and seasonality in northern New Zealand linked to Southern Hemisphere summer insolation

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ARTICLE INFO

Article history:

Received 20 August 2018

Received in revised form

8 October 2018

Accepted 9 October 2018

Available online 20 October 2018

Keywords:

Holocene

Paleoecology

Northern New Zealand

Southern hemisphere

Palynology

Chironomids

Insolation

Summer energy

ABSTRACT

The Holocene thermal maximum (HTM) is a spatio-temporally variable period of generally warmer conditions during the early and middle Holocene that is often used as an analogue for future climate change. Global scale climate reconstructions and models tend to smooth out the variations and complexity of the HTM and inconsistencies between reconstructions from different locations and proxies are often attributed to bias arising from different locations or proxies. We use these differences as a source of information about seasonality and precipitation during the Holocene in a multi-proxy investigation of the sediments of Lake Pupuke, northern New Zealand. The sediments, spanning the last 16 kyr, were analysed for pollen, from which mean annual air temperatures (MAAT) and effective precipitation were estimated, and chironomids, from which summer air temperature (SmT) was estimated. We found no evidence for an HTM in the MAAT reconstruction, questioning the validity of treating the early-to-mid Holocene as an analogue for future climate change in northern New Zealand. SmT increases between 10 and 3 cal kyr BP, correlating strongly with integrated local summer insolation. Early-Holocene low seasonality (from 12 to 9.3 cal kyr BP) was likely driven by low local summer insolation intensity. An early-to-mid-Holocene wet period (9.6–7.5 cal kyr BP) corresponds to relatively high southern westerly wind (SWW) strength. Mid-to-late-Holocene summers following the wet period were hot and dry, especially 4.0–2.4 cal kyr BP, allowing the tall conifer, kauri (*Agathis australis*) to expand throughout northern New Zealand. Low effective precipitation at this time is consistent with increased evapotranspiration due to higher SmT, although reduced precipitation due to southward displaced SWW or increased El Niño frequency may also have contributed.

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1. Introduction

Proxy records provide valuable information on past climate changes and a test for climate model simulations that aim to improve our understanding of the mechanisms that drove these changes (Renssen et al., 2005). Yet, model-data comparisons do not always agree (e.g. Liu et al., 2014) and improvements in both domains are necessary. The inability of models to simulate reconstructed past warm climate intervals in particular, and therefore future climate change, highlights the importance of exploring more

proxy reconstructions of those warm intervals that may be analogous to climate scenarios projected for the coming decades (Masson-Delmotte et al., 2013; Fischer et al., 2018).

One such period is the Holocene thermal maximum (HTM), which is loosely defined as an interval of generally warmer conditions spanning 11–5 kyr (Fischer et al., 2018). However, direct comparisons are complicated, because the HTM was asynchronous in its spatio-temporal expression: the warm period is best expressed in the higher northern latitudes, earliest in the North Pacific marine sector and delayed on land areas influenced by residual ice, especially the North Atlantic and Greenland regions. These regional complexities are typically smoothed out in global climate reconstructions, where inconsistencies between reconstructions from different proxies and locations are regarded as

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biases to be avoided (e.g. [Marcott et al., 2013](#)). On the other hand, the differences between proxy signals and records from different regions can be informative ([Sikes et al., 2013](#)). For instance, the seasonal bias in the differential response of multiple proxies to an environmental factor such as temperature may be used to reconstruct past seasonality.

We must also consider that the various spatio-temporal inconsistencies in global climate reconstructions may represent variable climate drivers in different areas of the globe. Although Northern Hemisphere summer insolation is often invoked to explain global climate signals (e.g. [Marcott et al., 2013](#)), the effect of local insolation parameters in other regions should not be overlooked ([Huybers and Denton, 2008](#)).

Here we aim to explore some of the complexity of the HTM and the structure of Holocene climate change in general using a suite of paleoclimate proxies developed from the sediments of Lake Pupuke, northern New Zealand ($36^{\circ}46'S$; [Fig. 1](#)). The 16-kyr record combines mean summer air temperatures (SmT) reconstructed from chironomid remains ([Dieffenbacher-Krall et al., 2007](#)) and mean annual air temperatures (MAAT) reconstructed from pollen assemblages ([Wilmshurst et al., 2007](#)), as well as an estimate of effective precipitation from those pollen assemblages ([Jara et al., 2017](#)).

The relevance of our record follows, firstly, from Lake Pupuke's southern mid-latitude position, which is a region that is strongly underrepresented in Holocene paleoclimate research ([Marcott et al., 2013](#)). Secondly, our multi-proxy approach involving both vegetation and aquatic insects sheds new light on changes in seasonality and effective precipitation. Thirdly, we compare our temperature reconstructions to insolation intensity at different latitudes in light of the ongoing debate over the role of local

insolation in Holocene temperature change and the HTM in particular ([Huybers and Denton, 2008](#); [Liu et al., 2014](#); [Marsicek et al., 2018](#)). Additionally, we draw attention to limitations in the current methodology for reconstructing past climate in New Zealand and suggest how these might be addressed with future work.

2. Study region

Auckland isthmus, together with immediately adjacent land areas to the north and south, is the location of both an active volcanic field (the Auckland Volcanic Field: AVF) and New Zealand's largest city ([Fig. 1](#)). Auckland region experiences a warm temperate, oceanic climate with few temperature extremes ([Chappell, 2014](#)). MAAT usually lies between 14 and $16^{\circ}C$, with mean temperatures in summer (Dec–Feb) around $19.5^{\circ}C$ and in winter (Jun–Aug) around $12^{\circ}C$ (data from the National Climate Database CLIDB: <https://cliflo.niwa.co.nz>). The distribution of precipitation in the Auckland region (totalling around 1100 – 1200 mm per year) shows a winter maximum, consistent with a more northern position of the high pressure belt north of New Zealand, which increases westerly airflow, compared to summer ([Chappell, 2014](#)). Unless otherwise specified, when we mention seasonality in subsequent text, we refer to the amplitude of temperature minima and maxima over a year (or the difference between mean summer and mean winter temperature), rather than this seasonality of precipitation.

New Zealand weather is strongly influenced by atmospheric circulation patterns that are dependent on a combination of broad scale climate modes, i.e. the Southern Annular Mode (SAM) and El Niño–Southern Oscillation (ENSO). [Kidston et al. \(2009\)](#) report a negative correlation between SAM and wind speed in New Zealand: during positive SAM, the southern westerly wind (SWW) belt

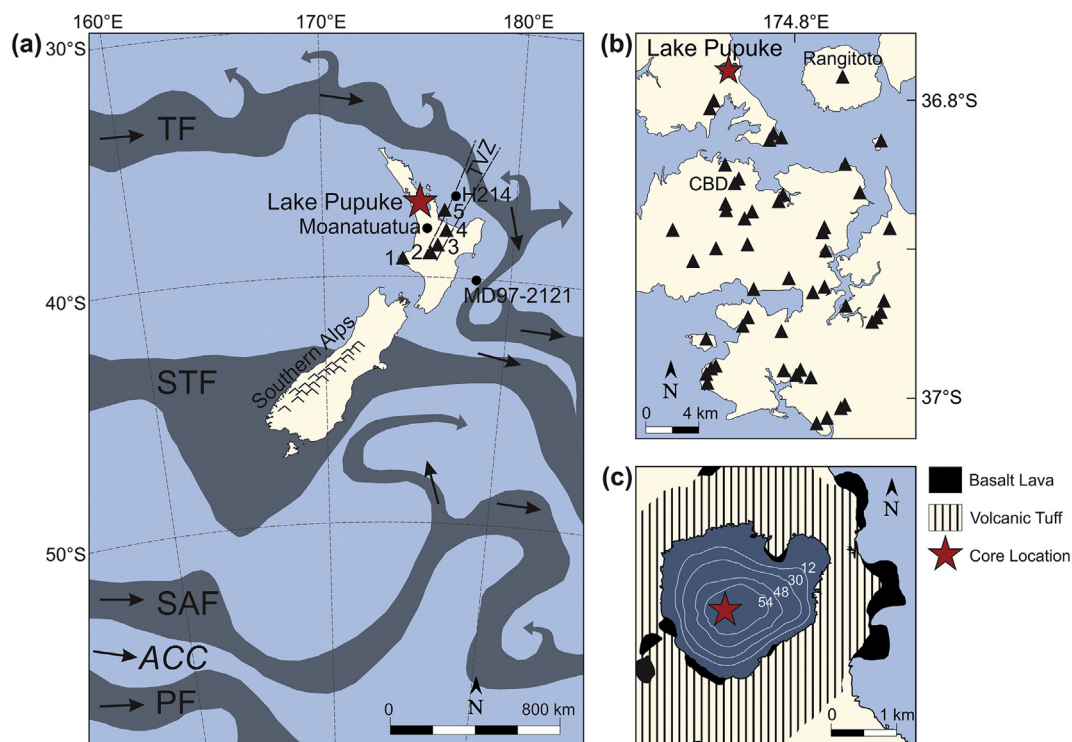


Fig. 1. Map of New Zealand, including surface water circulation (based on [Prebble et al., 2017](#)) and locations and core sites mentioned in the text (a), map of Auckland Volcanic Field (adapted from [Hopkins et al., 2017](#)) (b) and map of Lake Pupuke with bathymetry (adapted from [Newnham et al., 2018](#)) and the location of the core site (c). TF = Tasman Front; STF = subtropical front; SAF = subantarctic front; PF = polar front; ACC = Antarctic circumpolar current. Star indicates our study site, Lake Pupuke; circles indicate other core sites; triangles indicate volcanic centres (1 = Egmont Volcanic Centre, 2 = Tongariro Volcanic Centre, 3 = Taupo Volcanic Centre, 4 = Okataina Volcanic Centre, 5 = Tuhua Volcanic Centre, TVZ = Taupo Volcanic Zone). CBD = Auckland's central business district.

contracts southwards, decreasing westerlies over New Zealand, but strengthening them in the core of the SWW belt. In the Auckland region, positive SAM is associated with fewer cyclones and more anticyclones, decreased precipitation, and increased temperatures (Kidston et al., 2009). Regarding ENSO, southwesterly airflow is enhanced during El Niño years, due to the northward displacement of the westerlies (Ummenhofer and England, 2007). El Niño reduces rainfall in the north of New Zealand, whereas during La Niña years, no significant anomalies appear for the North Island (Kidson and Renwick, 2002; Ummenhofer and England, 2007).

Although the region is now urbanised, the natural vegetation cover can be deduced from isolated remnants (Wardle, 1991) and Holocene palynological records (Newnham and Lowe, 1991; Newnham et al., 2018). Prior to human settlement, ~750 yr BP (Newnham et al., 2018), the area supported extensive conifer-broadleaf forests, which are temperate rainforests that are dominated by either podocarps (rimu-rātā or podocarp-broadleaf forest) or *Agathis australis* (kauri forest). Both types of forest are multi-tiered with abundant lianas, epiphytes and tree ferns in the canopy and subcanopy layers (McGlone et al., 2016). In rimu-rātā forest, *Dacrydium cupressinum* (rimu) and *Metrosideros robusta* (northern rātā) are the major emergent species with, among others, *Beilschmiedia tawa* (tawa), *Nightia excelsa* (rewarewa), *Elaeocarpus dentatus* (hināu) and *Weinmannia silvicola* (tōwai) in the canopy layer. Tree ferns (*Cyathea* spp. and *Dicksonia* spp.) characterise the subcanopy and ferns the forest floor. Kauri forest is similar in structure and composition, but *Agathis australis* (kauri) and *Phyllocladus trichomanoides* (tanekaha) dominate the canopy, and the proportion of species that are part of the northern endemic group (e.g. *Beilschmiedia tarairi*, *Ixerba brexioides*) is much higher. Coastal forests in the Auckland region support *Metrosideros excelsa* (pōhutukawa), *B. tarairi* and *Dodonaea viscosa* (akeake). Beech forests (with *Fuscospora* spp. and *Lophozonia menziesii*) are generally absent from Auckland northwards, apart from some isolated stands (Wardle, 1991).

The AVF comprises 53 Quaternary basaltic centres located within a 600 km² area (Hopkins et al., 2017, Fig. 1b) and includes several maar craters that have provided a depositional environment for the accumulation of lacustrine sediments. Lake Pupuke (36°46'49"S, 174°45'57"E; Fig. 1c) is the only such crater that still contains a freshwater lake today and, as a consequence, is unique in having a sedimentary record covering the entire Holocene. The crater's estimated age is c. 193 kyr (Leonard et al., 2017), making it one of the oldest, if not the oldest, AVF volcanoes. The lake is a closed system, fed only by precipitation, with no significant inflows or outflows, a total surface area of 1.1 km², volume of 2.9 km³ and maximum depth of 57 m (Horrocks et al., 2005). The lake supports submerged macrophytes (Coffey and Clayton, 1987), is classed as moderately eutrophic (Cassie, 1989) and is stratified during summer (Horrocks et al., 2005).

3. Methods

3.1. Drilling, chronology, and sampling

Lake Pupuke was cored in February 2007 using an UWITEC drilling platform and fixed-piston coring system. The resulting 16 short, overlapping cores span 16.1 m of sediment with a diameter of 59 mm (Stephens et al., 2012a; b). Only the top 7.1 m representing the last ~16 kyr were analysed in this study. Sediment cores were split lengthwise, after which one half was cut into 1-cm wide wedges and bagged. Both working and archive halves were stored at 4 °C and subsampled further between 2015 and 2017 for the palynological and chironomid analyses presented here.

The 16.1-m sequence is estimated to extend to 48.2 ± 4.7 cal kyr

BP (Stephens et al., 2012a) and is laminated throughout, although the laminae are not considered to be annually deposited (Striewski et al., 2013). The sequence contains basaltic tephra layers with an AVF source and distal tephra layers from central North Island sources: rhyolitic tephra from Taupo Volcanic Zone, and andesitic tephra from Egmont volcano and the Tongariro Volcanic Centre (Fig. 1a and b).

In this study, a revised chronology was established for the top 7.1 m of the core, incorporating the youngest basaltic tephra layer: Rangitoto-1/2 (Needham et al., 2011; Newnham et al., 2018) and a newly modelled age for Tuhua tephra (Lowe, D.J., pers. comm.), while ages reported by Lowe et al. (2013) were used for the other rhyolitic tephra layers (Table 1). We also modelled the radiocarbon dates from Stephens et al. (2012a, b), which were recalibrated in OxCal v.4.3 (Bronk Ramsey, 2009a) using the SHCal13 (Hogg et al., 2013) calibration curve (Table 2). However, as with previously reported ¹⁴C dating at Lake Pupuke, these proved to be problematic due to old carbon effects (Horrocks et al., 2005; Newnham et al., 2018) and the chronology of the core was instead based solely on tephrostratigraphy. The age-depth model was calculated using the *P_Sequence* model (Bronk Ramsey, 2008; Bronk Ramsey and Lee, 2013) with 1 interpolation per cm. The "TSimple" outlier model was used (Bronk Ramsey, 2009b), where the outlier distribution is normal ($\mu = 0$, $\sigma = 100$) and each measurement has a prior probability to be an outlier of 5%. This outlier model is appropriate for non-radiocarbon measurements and allows for a temporal offset of ~ one hundred years between primary deposition of the tephra and final location in the core.

Samples for the period from 16 cal kyr BP to the present were selected for pollen and chironomid analyses from the stored 1-cm wide wedges that were cut from the cores in 2007. Additional subsamples were taken from the archived half of the core where necessary. This sampling strategy was aimed at deriving regularly spaced time intervals, although subsequent age modelling resulted in irregularly spaced intervals. Sample resolution averages 230 cal yr BP (range: 13–794 cal yr BP).

3.2. Palynology

For pollen analysis, 0.5-to-0.75-mL subsamples were obtained and prepared according to standard procedures (Moore et al., 1991), which include a hydrochloric acid step to remove carbonates, potassium hydroxide step to remove humic acids, density separation with a sodium polytungstate solution (specific gravity: 2.2), and acetolysis to remove cellulose. One *Lycopodium* tablet with a known number of spores was added to each sample to allow for the calculation of pollen concentrations. The processed material was mounted on microscope slides in glycerine jelly and analysed under a light microscope at 400x or 1000x magnification. Grains were identified with the aid of Moar (1993), Pocknall (1981) and modern reference slides, applying the naming convention suggested by Moar et al. (2011). We counted 250 pollen sum grains per sample, where the pollen sum includes dryland pollen and *Pteridium* spores but excludes wetland taxa and other spores. Taxa were expressed as percentages of the pollen sum.

The pollen diagram was plotted in R (version 3.3.1; R Core Team, 2016) using the package "rioja" (Juggins, 2015) and zonation was established by visual assessment and aided by applying stratigraphically constrained cluster analysis (CONISS method) to all pollen sum taxa. Rare taxa (with a maximum abundance of <1%) were excluded from the figure to improve legibility, but included in the cluster analysis.

We chose pollen as a proxy appropriate for the reconstruction of MAAT and effective precipitation. For quantitative MAAT reconstructions, the weighted averaging modern analogue technique

Table 1

Tephra layers included in the age-depth model and their sources (see Fig. 1a and b).

Tephra name	Type	Source	Depth (cm)	Age (cal yr BP $\pm 2\sigma$)	Reference
Rangitoto-1/2	Basaltic	AVF	84	530 ± 31	Needham et al., 2011
Taupo	Rhyolitic	Taupo VC	205	1718 ± 10	Lowe et al., 2013
Tuhua	Rhyolitic	Tuhua VC	399	7637 ± 100	Lowe, D.J., pers. comm.
Rotoma	Rhyolitic	Okataina VC	465	9423 ± 120	Lowe et al., 2013
Waiohau	Rhyolitic	Okataina VC	618	14009 ± 155	Lowe et al., 2013
Rotorua	Rhyolitic	Okataina VC	653	15635 ± 412	Lowe et al., 2013
Rerewhakaaitu	Rhyolitic	Okataina VC	701	17496 ± 462	Lowe et al., 2013

Table 2

AMS radiocarbon ages from Lake Pupuke sediments.

Laboratory number ^a	Depth (cm)	Conventional radiocarbon age (yr BP $\pm \sigma$)	Calibrated median age (cal yr BP)	95.4% confidence intervals (cal yr BP)
NZA33095	442	8346 ± 35	9306	9040–9043 9089–9475
NZA33683	483	10124 ± 45	11638	11292–11299 11305–11986
NZA33096	512	10604 ± 45	12514	12108–12227 12266–12340 12367–12704
OZK258	554	10662 ± 104	12475	11834–11884 11933–12984
NZA33097	585	11673 ± 45	13458	13275–13634 13669–17709
NZA33098	640	13126 ± 50	15678	15316–16006

^a NZ: Rafter Radiocarbon Lab, New Zealand; OZ: ANSTO-ANTARES, Australia.

(MAT) (10 closest analogues; $RMSEP_{boot} = 1.51$, $r^2_{boot} = 0.82$) and partial least squares (PLS) model with 2 components ($RMSEP_{boot} = 1.50$, $r^2_{boot} = 0.77$) were applied to the pollen percentage data, using the New Zealand pre-deforestation pollen dataset described in detail by Wilmschurst et al. (2007). MAAT was found by Wilmschurst et al. (2007) to have the best predictive success in the pollen dataset, and has been reconstructed in many other studies, e.g. McGlone et al. (2010a), Newnham et al. (2012), Sikes et al. (2013) and Jara et al. (2017). Newnham et al. (2013) discuss the strengths and weaknesses of the pre-deforestation pollen training set extensively. The pollen database covers a MAAT gradient from 3.2 to 16.1 °C, encompassing all temperatures reconstructed for Lake Pupuke. MAAT was not reconstructed for samples younger than 1000 cal yr BP as anthropogenic impacts have compromised the modelled pollen-climate reconstructions (Wilmschurst et al., 2007). A Generalised Additive Model (GAM) was fitted to the reconstructed MAAT over time to show a best fit through the data, using R package “mgcv” (Wood, 2006, 2011). Although we are mindful that certain plant species are sensitive to minimum temperatures, mean annual temperature has been found to have better predictive success than seasonal temperature in the training set (Wilmschurst et al., 2007). Therefore, the transfer function was calibrated to MAAT and we assume that pollen assemblages are representative of MAAT but recognise that variability in some taxa may correspond to minimum temperature and the prevalence of frosts, despite these being rare in the region today.

Additionally, some key New Zealand pollen taxa show sensitivity to precipitation and drought (Wilmschurst et al., 2007). We calculated the Pollen Moisture Index (PMI) as the normalised, base-10 logarithm of the ratio of *Dacrydium cupressinum* percentages over the percentage of *Podocarpus* and *Prumnopitys* spp., following Jara et al. (2017). The PMI is based on the “rimu ratio” (the abundance of *D. cupressinum* pollen over other tree podocarps), which has previously been used to infer moisture conditions (McGlone and Topping, 1977; Newnham et al., 1995). *D. cupressinum* is less tolerant of droughts and more tolerant of

waterlogged soils than other tree podocarps (Franklin, 1968), and its abundance correlates negatively with October vapour pressure deficit, a measure of spring humidity (Wilmschurst et al., 2007). Therefore, PMI can be considered an indicator of effective precipitation: the amount of rainfall that gets absorbed into the soil. Effective precipitation is a function of total precipitation and evaporation and reflects available moisture for plant growth. A GAM was fitted to the reconstructed PMI to show a best fit through the data.

3.3. Chironomid analysis

For chironomid analysis, 0.5–6.5 mL of sediment was prepared according to standard procedures (Walker et al., 1991). Samples were deflocculated in hot 10% KOH for 15 min and then sieved over a 90- μ m nylon mesh. The exact volume of sediment was selected to retrieve at least 50 whole head capsules per sample (Heiri and Lotter, 2001). After sieving, head capsules were picked from the residue in a Bogorov tray under 50x magnification and mounted onto slides, which were fixed with “Norland Optical Adhesive 61”. Chironomid taxa were then identified using a light microscope at 400x magnification. In addition, occurrences of mites, bryozoan oocytes, Ceratopogonidae, Characeae oospores, cladoceran ephippia and Ephemeroptera mandibles were counted. All taxa were expressed as percentages of the total number of chironomids.

The chironomid diagram was plotted in R (version 3.3.1; R Core Team, 2016) using package “rioja” (Juggins, 2015) and zonation was established by visual assessment and aided by applying stratigraphically constrained cluster analysis (CONISS method) to all chironomid taxa. To aid in interpretation of the chironomid record, taxa were assigned to either “cold-adapted taxa” or “warm-adapted taxa”, based on their affinity (β coefficient; see Supplementary Information 1, Table S1.2) with SmT (Dieffenbacher-Krall et al., 2007). Four taxa, i.e. *Cryptochironomus*, *Harrisius*, *Pentaneurini* 1 and *Xenochironomus*, do not have a β coefficient (too rare in training set) and were therefore plotted under “unassigned”.

For summer temperature (SmT) reconstruction, we used the Dieffenbacher-Krall et al. (2007) chironomid inference model. This model was developed from South Island lakes and covers a SmT gradient from ~ 6 to 16°C , which falls short of the modern SmT at Lake Pupuke ($\sim 19.5^\circ\text{C}$). As a consequence, reconstructions of SmT from the northern North Island may be underestimated and, whilst trends and relative differences should be robust, in absolute reconstructed temperatures should only be used with this limitation in mind.

The original training set was adapted, i.e. we did not distinguish between “short” or “long” antennal pedestal variants of both *Tanytarsus funebris* types A and C. To select the best performing model, the weighted averaging-partial least squares (WA-PLS) approach was compared to the PLS method; for a description of the model diagnostics, see Supplementary Information 1; WA-PLS was chosen as it was shown to perform better than PLS. The model was run in R (version 3.3.1; R Core Team, 2016) using package “rioja” (Juggins, 2015). Rare taxa (number of occurrences < 2 or maximum abundance $< 1\%$) were excluded; percentages were square root transformed. After the best performing model was selected, past SmT was reconstructed from our fossil chironomid assemblages. To test the reliability of the inferred temperatures, the goodness of fit of the samples compared to the training set was assessed (Birks et al., 1990), as well as the abundance of rare (Hill's $N2 \leq 5$; Hill, 1973; Brooks and Birks, 2001) and absent taxa in each sample. A GAM was fitted to the reconstructed SmT over time to show a best fit through the data, using R package “mgcv” (Wood, 2006, 2011).

3.4. Goodness of fit

To test the reliability of the temperature reconstructions, the goodness of fit of the samples compared to the training sets was assessed for both the MAAT and SmT reconstructions (Birks et al., 1990), as well as the abundance of rare taxa. Goodness of fit was determined by comparing the squared residual distance of the training set samples from an ordination axis constrained by temperature to the squared residual distance of the fossil samples that were passively fitted to the same axis (using R package “analogue”; Simpson, 2007; Simpson and Oksanen, 2016). The fit is considered to be poor if the squared residual distance of a sample is greater than the 90th percentile of the squared residual distances of the training set samples and very poor if it is greater than the 95th percentile (Birks et al., 1990). Rare taxa are defined as taxa that have a Hill's $N2$ (Hill, 1973) of 5 or less in the training set (Supplementary Information 1, Table S1.1 and S1.2; Brooks and Birks, 2001). Additionally, to test the reliability of the modern analogue technique, the dissimilarity between pollen assemblages from the Pupuke samples and the closest modern analogue in the training set was calculated. If samples have a dissimilarity greater than the 5th percentile of the distribution of dissimilarities between training set samples, they are considered to have no close modern analogue (Simpson, 2007; Simpson and Oksanen, 2016).

4. Results

4.1. Chronology

The new age-depth model of the Lake Pupuke core ranges from 711 to 0 cm depth, and from 17,500 to -57 cal yr BP (Fig. 2). It includes 7 tephra ages (Table 1) but excludes the radiocarbon dates (Table 2), as many of them had older than expected ages (875 yr older on average), likely caused by a previously described old carbon effect in the Lake Pupuke sediments (Horrocks et al., 2005).

The 95.4% range for modelled ages varies, but averages around 2130 years, which is equivalent to a c. 1000 yr estimated $2\text{-}\sigma$ error.

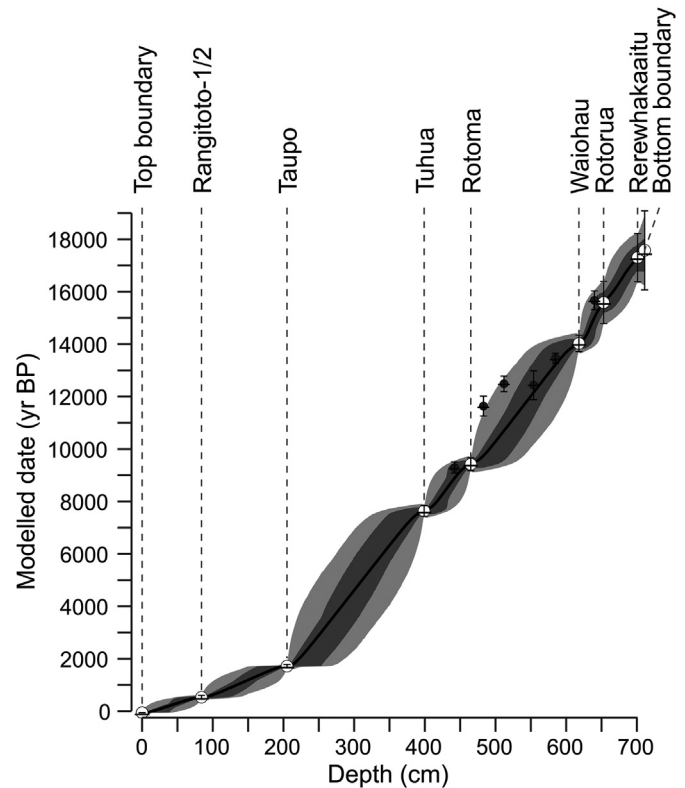
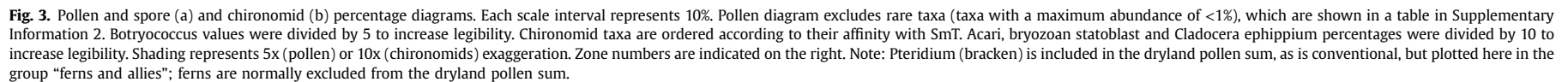


Fig. 2. Age-depth model for the Lake Pupuke core. The line indicates the median age per depth, dark grey area indicates the 68.2% confidence interval and light grey area indicates the 95.4% confidence interval. Tephra dates (names at top) are plotted with a white symbol at their mean age and a dash at their median age; error bars indicate the $2\text{-}\sigma$ error. Radiocarbon dates were plotted passively (black symbols).

The 95.4% range is narrower during the last 2 cal kyr BP, i.e. c. 700 years (350 yr $2\text{-}\sigma$ error). The model predicts three time intervals with different sedimentation rates, i.e.: $\sim 0.35 \text{ mm.yr}^{-1}$ for the period between 18.0 and 1.8 cal kyr BP, $\sim 1.0 \text{ mm.yr}^{-1}$ for 1.8 to 0.6 cal kyr BP, and $\sim 1.4 \text{ mm.yr}^{-1}$ for the last 600 years.

4.2. Pollen record

The pollen record (Fig. 3a) is divided into four CONISS zones (PZ1–4) with boundaries at 12.3, 6.7 and 0.5 cal kyr BP. PZ1 to PZ3 show persistently high percentages of forest taxa ($\sim 84\%$) with varying composition. PZ1 shows the gradual decline of conifer-beech forest as *Dacrydium cupressinum* rises to dominance (from 24 to $\sim 32\%$). During PZ2a (from 12.3 cal kyr BP), *Prumnopitys taxifolia* declines (from ~ 15 to 5%) while other taxa, notably *Metrosideros* and *Ascarina lucida*, become more abundant (on average 7% and 3% respectively), indicating the development of podocarp-broadleaf forest (rimu-rātā forest); PZ2b (from ~ 9.3 cal kyr BP) shows further development of this forest along with an increase in *Dodonaea viscosa* (from 1 to 4%). The onset of PZ3 (~ 6.7 cal kyr BP) coincides with the sudden rise to prominence of *Agathis australis* (from 1 up to 36%) at the expense of *Dacrydium cupressinum* (which declines to $\sim 18\%$), signalling the advance of kauri forest. PZ4 (0.5 cal kyr BP to present) represents the beginning of human influences at the site and is characterised by a sustained increase in *Pteridium* and shrub and herb taxa (e.g. *Coprosma*, *Coriaria*, *Poaceae*) to $\sim 40\%$, followed by the appearance of exotic taxa (e.g. *Pinus*, *Plantago lanceolata*) signalling the onset of the European era. For rare taxa (maximum abundance $< 1\%$), see Supplementary Information 2.



4.3. Chironomid record

The chironomid record (Fig. 3b) is divided into five CONISS zones with boundaries at 9.6, 6.7, 0.9 and 0.7 cal kyr BP. The three samples older than 14.1 cal kyr BP contained virtually no chironomid remains. The samples at 14.1 and 13.6 cal kyr BP yielded sums of just 13.5 and 29.5, respectively. Nevertheless, they were included in all analyses, but interpretations of them are made with caution as these concentrations fall below the $n = 50$ threshold. Chironomid Zone (CZ) 1 is dominated by cold-associated taxa (54%) such as *Macropelopini* types (combined ~20%) and *Tanytarsus funebris* type C (~10%). CZ2 (from 9.6 cal kyr BP) displays the rise of warm-associated *Cricotopus aucklandensis* from 3 to 18%, which continues to rise through CZ3a (from 6.7 cal kyr BP) up to 47% as cold-associated taxa (notably *Tanytarsus vespertinus*) decline. Zone CZ3b (0.9–0.7 cal kyr BP) contains only two samples and is characterised by a spike in *Polypedilum* (42–60% vs. on average 8% in other zones); *Polypedilum* is a cosmopolitan, speciose taxon whose high abundance is difficult to interpret. CZ4 (0.7 cal kyr BP to present) shows relatively high percentages of cold-associated taxa, such as *Tanytarsus funebris* type A and C (~14% combined vs. ~4% in CZ3a), and *Chironomus* (7% vs. 1% in CZ3a); its timing overlaps with the human era.

4.4. Climate reconstructions

All pollen samples have close modern analogues in the training set (all have dissimilarities <5th percentile value of the dissimilarity distribution of the training set samples; Fig. 4a) and all but two show a good fit to MAAT (Fig. 4b). Only the samples at 1669 and 8528 cal yr BP show a squared residual higher than the 90th percentile value of the training set squared residuals (= 5.30) and are therefore considered poorly fitted to MAAT. There are 8 samples with a high abundance (>5%) of rare taxa and/or taxa that are not included in the model (Fig. 4a and b). These are samples with high

abundances of *Dodonea viscosa*, which is rare in the training set (Supplementary Information 1, Table S1.1). The two MAAT reconstructions show similar trends throughout the record (Fig. 5a and b). Temperatures increase rapidly, i.e. from ~9 to 13 °C between 16.0 and 12.3 cal kyr BP, and more gradually between 12.3 and

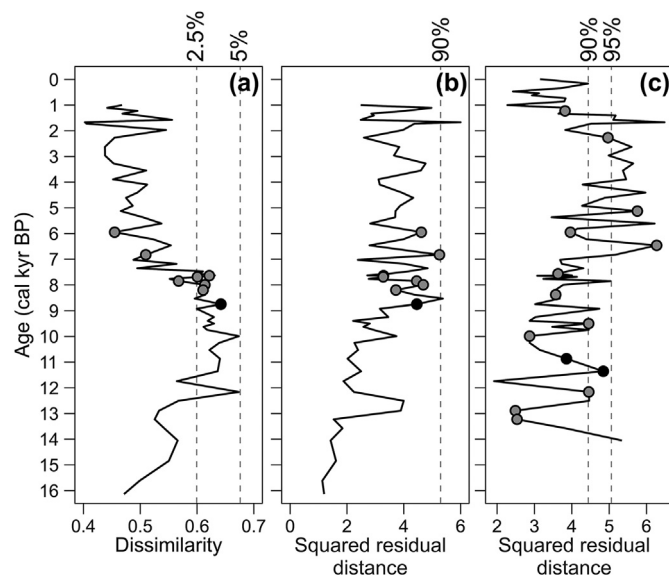


Fig. 4. Reconstruction diagnostics. Dissimilarity of pollen assemblages to modern analogues (a) with vertical lines representing percentiles of the distribution of the pair-wise dissimilarities for the training set samples. Goodness of fit over time of pollen samples (b) and chironomid samples (c) to MAAT and SmT respectively, with vertical lines representing percentiles of the squared residual distances of training set samples. Samples with >5% rare taxa (Hill's N2 in training set ≤ 5) and those taxa not included in the inference model are indicated with grey symbols, >7.5% with black symbols.

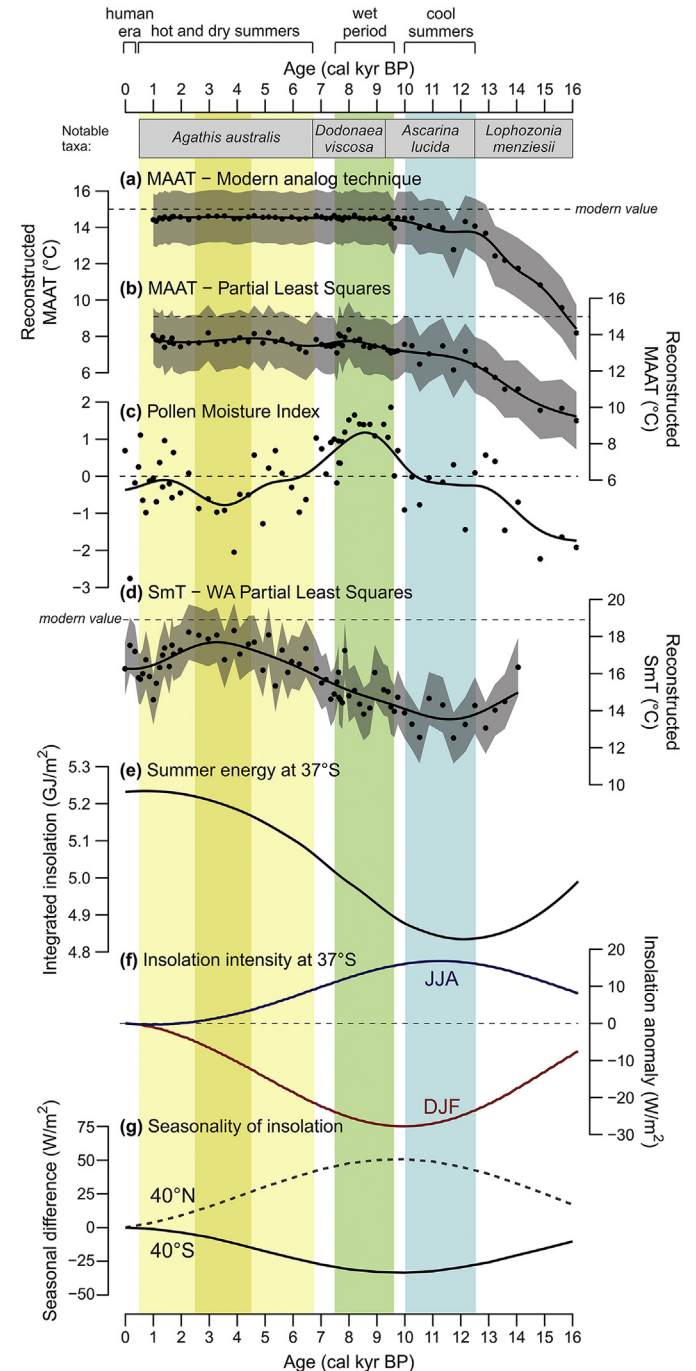


Fig. 5. Synthesis record including reconstructions of MAAT (modern analogue technique (a) and partial least squares method (b)), effective precipitation (PMI) (c), and SmT (d); points are reconstructed values, line is generalised additive model, shaded areas represent transfer function error (RSMEP). Comparison to insolation parameters: integrated summer insolation ("summer energy") at 37°S with a threshold τ of 425 W/m² (e), average insolation intensity anomaly at 37°S of December, January, February (DJF) and July, June, August (JJA) (f), and seasonal insolation differences: insolation in DJF less insolation in JJA at 40°S and insolation in JJA less insolation in DJF at 40°N (g). Insolation parameters from: Berger and Loutre (1991), Huybers (2006), and Huybers and Eisenman (2006).

10.0 cal kyr BP. After 10.0 cal kyr BP, the modern analogue technique shows a stable MAAT of $\sim 14.5^\circ\text{C}$, while the partial least squares method produces a lower Holocene MAAT ($\sim 13.6^\circ\text{C}$).

The PMI, a non-quantitative reconstruction of effective precipitation, shows a phase from dry to increasingly wet conditions between 16 and ~ 13 cal kyr BP, followed by a plateau between 13 and 10 cal kyr BP (Fig. 5c). A wet interval occurs between 9.6 and 7.5 cal kyr BP, before PMI gradually decreases, indicating a drying trend, with a minimum around 3.5 cal kyr BP, before increasing again. PMI values are most variable after ~ 2 cal kyr BP.

For chironomid-derived SmT estimates, we chose the 3-component WA-PLS model ($\text{RMSEP}_{\text{jack}} = 1.21$, $r^2_{\text{jack}} = 0.81$) as it displayed lower bias at the higher end of the SmT gradient compared to the PLS model (see Supplementary Information 1). The goodness-of-fit test shows that the fossil chironomid record contains 11 samples that are poorly fitted to SmT ($\sim 16\%$ of all samples), and 13 samples that are very poorly fitted ($\sim 19\%$ of all samples; Fig. 4c). There are 8 samples with a high abundance ($>5\%$) of rare taxa and/or taxa that are not included in the model. The distribution of these samples seems unrelated to the goodness of fit (Fig. 4c). Instead, the samples with a very poor fit include the oldest sample (which had a count sum of only 13.5) and samples with a high reconstructed SmT. The reconstructed SmT is lowest between c. 12.5 and 10.0 cal kyr BP (mean = 14.4°C ; Fig. 5d). From ~ 11.5 cal kyr BP, SmT increases until the highest temperature is reached around 3 cal kyr BP ($\sim 18^\circ\text{C}$). Afterwards it rapidly declines to $\sim 16^\circ\text{C}$. As expected, because the modern training set is based on South Island lakes, reconstructed temperatures are all well below modern day SmT at Lake Pupuke (which is $\sim 19.5^\circ\text{C}$).

5. Discussion

5.1. Palaeoecological reconstructions

5.1.1. Pollen

The earliest phase of the pollen record (16–12.3 cal kyr BP) depicts a progressive transition from more open mixed conifer-beech forest with prominent shrub understorey to a more closed forest. Previous pollen records from Auckland that trace the vegetation changes of the region during the LGM and subsequent deglacial transition (Sandiford et al., 2002, 2003; Newnham et al., 2007) show very similar trends for this period, and in particular the progressive decline of beech and shrub components. During the early-to-mid Holocene, beech virtually disappears as rimu-rātā forest becomes the dominant vegetation in the region. The expansion of the small, predominantly coastal tree *Dodonaea viscosa* occurs from around 9 cal kyr BP, and is consistent with the approaching culmination of postglacial sea level rise (~ 7 –8 cal kyr BP; Clement, 2016) and the establishment of coastal conditions at the study site. The most prominent change in the vegetation record occurs at ~ 7 cal kyr BP with the expansion of kauri forest, presumably extending into areas previously supporting rimu-rātā forest. Previous pollen records from the AVF region have shown this kauri expansion, along with the other Holocene vegetation changes depicted in the Lake Pupuke record (e.g. at Lake Waatarua, Newnham & Lowe, 1991; Mt Richmond, Sandiford et al., 2002; Pukaki Crater, Sandiford et al., 2003; Onepoto maar, Augustinus et al., 2011, 2012; and a previous study on Lake Pupuke that focussed on the last ~ 9 cal kyr BP, Horrocks et al., 2005), although exactly why this profound change developed from this time remains unclear.

These pollen-vegetation reconstructions are important in helping to evaluate the MAAT reconstructions derived from them. Despite the marked change in vegetation composition, MAATs are comparatively stable after ~ 10 cal kyr BP (see section 5.2 for

comparison to other records). We note that the dominant pollen taxa involved are all correlated strongly with MAAT in the training set (i.e. r values: 0.59 for *Agathis australis*, 0.57 for *Metrosideros*, 0.51 for *Dacrydium cupressinum*; from Wilmshurst et al., 2007). Additionally, all samples display pollen assemblages with close modern analogues in the pollen training set (Fig. 4a), and all but two show a good fit with MAAT (Fig. 4b). We suggest therefore that MAAT by itself was not a factor in these marked vegetation changes and in section 5.3 explore other climate parameters that may have been important.

5.1.2. Chironomids

The chironomid record shows that warm-associated taxa gradually replace cold-associated taxa over time, with a peak in warm-associated taxa between 4 and 2 cal kyr BP (Fig. 3b). This pattern is mostly driven by the increase of *Cricotopus aucklandensis* (β coefficient: 26.6) and decline of *Tanytarsus funebris*, type C (β coefficient: 10.8). Dieffenbacher-Krall et al. (2007) found that SmT is the dominant environmental variable that shows a strong relationship with chironomid abundances. Other variables that were found to be associated with chironomid abundances include conductivity, chlorophyll *a* and organic content of the sediments. There is no stratigraphic or palaeoecological evidence to suggest that these other factors were important in the Lake Pupuke chironomid record. The sediments are laminated consistently throughout, with no visible variations. Lake depth is another variable that has been linked to changes in chironomid assemblages (e.g. Engels et al., 2016), but as Lake Pupuke is currently ~ 57 m deep any changes in lake level throughout the Holocene were likely to have been relatively small. Additionally, because the basin is steep sided, changes in the size of the littoral area due to lake level changes are also unlikely to have been significant. These considerations support our confidence in the SmT reconstructions from Lake Pupuke, but we acknowledge that these other local site variables may also have influenced the chironomid assemblages.

The SmT transfer function we applied to our chironomid data was developed from South Island lakes and covers a SmT gradient from ~ 6 to 16°C (Dieffenbacher-Krall et al., 2007). This is not ideal for reconstructing SmT at Lake Pupuke, where modern day mean temperature for the summer months is $\sim 19.5^\circ\text{C}$. The absence of training set lakes from the warmer North Island may shift taxon optima towards the cooler end of the SmT gradient and reconstructions from Lake Pupuke may be underestimated. This is confirmed by our goodness-of-fit test, which shows that samples with a high reconstructed SmT display a very poor fit (Fig. 5b). This limitation should be borne in mind for any consideration of the absolute reconstructed temperatures above 16°C from Lake Pupuke. Nonetheless, we suggest that the trends and relative changes in SmT are robust reconstructions. We also point out that the poorly fitted samples that display high temperatures are also the samples with high abundances of *Cricotopus aucklandensis*, which is one of the taxa most strongly associated with high SmT.

Our SmT reconstruction from Lake Pupuke highlights the lack of North Island lakes in the current chironomid training set and associated difficulty the model has with reconstructing high SmT. This work demonstrates the importance of undertaking future work aimed at expanding the chironomid training set with data from northern New Zealand sites.

5.2. Temperature reconstructions in a regional and global context

Our Lake Pupuke record shows that after the Last Glacial–Interglacial transition, from ~ 12 cal kyr BP, MAAT stabilises around 14.5°C , within the range of modern MAAT at the site (Fig. 5a and b). There is no evidence for a Holocene Thermal Maximum

(HTM), which is consistent with mean annual sea surface temperatures (SST) inferred from nearby marine records (i.e. H214 and MD97-2121, Fig. 1a; Prebble et al., 2017). Prebble et al. (2017), studied seven marine records on a meridional transect of the southwest Pacific Ocean and found that only records in the region immediately south of the subtropical front display an early-Holocene warm peak, while records along the east coast of the North Island show stable SSTs throughout the Holocene. The stability of our reconstructed Holocene MAAT is inconsistent with the regional temperature reconstruction for the southern mid latitudes reported by Marcott et al. (2013), which shows an early-Holocene maximum (as does the global mean temperature reconstruction). In light of our results and the observations of Prebble et al. (2017), we suggest that the regional temperature reconstruction for the southern mid latitudes reported by Marcott et al. (2013) may reflect records from sites that are predominantly located between the subtropical front and polar front. Alternatively, the modern relationship between vegetation and MAAT may have broken down during the early Holocene under the influence of secondary, confounding variables, such as minimum temperatures or precipitation (see section 5.3). However, we have no way to test or control for this and must therefore keep the limitations of the model in mind.

In the Northern Hemisphere, North Atlantic SST records show a very clear HTM during the early Holocene, followed by a cooling trend (Marcott et al., 2013), in line with declining northern summer insolation throughout the Holocene. Marsicek et al. (2018) find a similar cooling trend in European and North American pollen records but only after ~5.5 kyr BP. They explain that the HTM and subsequent cooling trend is delayed in continental records compared to the SST records in this region, because remnant ice sheets caused continental air temperature depression during the early Holocene. Subsequent warming is in line with model simulations forced by declining albedo, elevation, and meltwater of ice sheets. The cooling trend, consistent with declining northern summer insolation, only commences after 5.5 kyr in the continental records (cf. Renssen et al., 2009).

This match between summer cooling and declining summer insolation in the Northern Hemisphere mirrors our findings for northern New Zealand. The SmT record from Lake Pupuke indicates that summers were cool during the early Holocene until ~10 cal kyr BP, and then warmed progressively until ~3 cal kyr BP (Fig. 5d). This warming trend is opposite to the Northern Hemisphere records, but in line with increasing summer insolation intensity at the southern mid-latitudes (Fig. 5f) and correlates well with total summer energy (integrated summer insolation of days whose diurnal average insolation >425 W/m²; Fig. 5e) (Berger and Loutre, 1991; Huybers, 2006; Huybers and Eisenman, 2006). The similarity of the SmT and local summer insolation records implies a causal relationship throughout the Holocene. Putnam et al. (2012) describe a similar inter-hemispheric mirroring pattern, where glacier behaviour in New Zealand's Southern Alps (Fig. 1a) correlates with southern summer insolation, whereas glaciers in the European Alps were found to respond to northern summer insolation forcing.

The observation that the expression of the HTM in different regions might be influenced by local insolation forcing and the presence or absence of ice sheets is not a new idea (e.g. Renssen et al., 2009; Fischer et al., 2018; Marsicek et al., 2018). Fischer et al. (2018) admit that the complex regional expression of the HTM makes it difficult to draw a unique global picture but argue that it can still serve as an example of regionally warmer conditions. However, our findings indicate that early Holocene climate might not offer an instructive analogue for the impact of future warming in northern New Zealand, because we do not find temperatures higher than present.

5.3. Seasonality and effective precipitation

Although the MAAT reconstruction from the pollen assemblage data is stable from 10 cal kyr BP onwards, there are distinct changes in vegetation throughout the Holocene (Fig. 3a), as has been observed previously in northern New Zealand (e.g. Newnham and Lowe, 1991; Sandiford et al., 2002, 2003; Horrocks et al., 2005; Augustinus et al., 2011, 2012). Specifically, *Metrosideros* and *Ascarina lucida* are abundant during the early Holocene, while *Dodonaea viscosa* rises from 9.3 cal kyr BP. The most pronounced change occurs at 6.7 cal kyr BP, when *Agathis australis* (kauri) abruptly becomes the dominant taxon at the expense of, among others, *Dacrydium cupressinum*. We propose these shifts are driven by changes in seasonality and effective precipitation (cf. Sikes et al., 2013).

The early Holocene (12.3–9.3 cal kyr BP) corresponds to the period of lowest reconstructed SmT, while MAAT has reached close to modern values. Our combined temperature records thus indicate low seasonality (cool summers and warm winters), conditions favourable to *Metrosideros* and *Ascarina lucida*, which have reached maximum abundances at this time. These angiosperm trees are frost sensitive and require high humidity (McGlone and Moar, 1977; Wilmshurst et al., 2007) so would have benefited from mild, moist winters. The PMI rises during this period to reach a peak at ~9 cal kyr BP, indicating moisture availability was unlikely to be a limiting factor. Low seasonality has previously been invoked to explain early Holocene vegetation patterns in New Zealand (e.g. Newnham and Lowe, 1991; Wilmshurst et al., 2002; McGlone and Basher, 2012; McGlone et al., 2010b; Jara et al., 2015) as well as other local trends (e.g. Stephens et al., 2012b). Our combined MAAT and SmT reconstructions support this hypothesis.

After the early Holocene, effective precipitation (PMI) increases, signalling a wet period between 9.6 and 7.5 cal kyr BP concomitant with a peak in *Botryococcus* algae and the rise of *Dodonaea viscosa*. Summer insolation intensity and seasonality are still relatively low at this time. The increase in *Botryococcus* is consistent with an expanded lake area and higher lake levels in response to increased precipitation. Jara et al. (2017) reconstruct a very similar period of wettest conditions at Moanatuatua (c. 140 km southeast of Lake Pupuke, at 38°S; Fig. 1a) between 10 and 6 cal kyr BP, confirming that the increase in effective precipitation is likely a regional phenomenon, rather than a local one.

Effective precipitation starts to decline along with rising summer temperatures from 7.5 cal kyr BP onwards. The warmest and driest conditions occur during the late Holocene, between ~4.0 and 2.4 cal kyr BP, when summer energy reaches peak values. The warm, dry summer conditions overlap with the rise in kauri abundance, which is a widespread phenomenon observed in northern New Zealand pollen records (e.g. Newnham and Lowe, 1991; Newnham, 1999; Ogden et al., 1992; Newnham et al., 1995). Less clear is why this profound shift occurred at this time, from around 7 cal kyr BP. Climatic explanations are confounded by the severely modified modern distribution of kauri, its longevity (often >600 years) and periodic regeneration (Ogden et al., 1992). Nevertheless, it has been established that kauri growth is enhanced during sunny, dry summers (September to April) (Ogden and Ahmed, 1989), conditions that are clearly shown in our temperature and effective precipitation reconstructions (Fig. 5c and d) as coinciding with the expansion of kauri during the mid-to-late Holocene. Previous climate inferences drawn from this kauri expansion could be questioned on grounds of circularity of argument, but in this case the SmT and PMI reconstructions are independent of the kauri pollen record.

5.4. Potential causes of wet and dry periods

The early-to-mid Holocene wet period followed by increasingly dry conditions as apparent from the PMI and the appearance of kauri, indicate that effective precipitation declined over time, which is in line with increasing evapotranspiration from 7.5 cal kyr BP onwards due to higher SmT. Alternatively, the decline in effective precipitation could have been caused by a decline in rainfall, consistent with a progressively southwards shifting SWW belt, causing westerly winds over New Zealand to decline (Kidston et al., 2009), while strengthening in the core. This is broadly in line with the findings of Moros et al. (2009) who report weaker westerlies and poleward shifting fronts in South Australia (~36°S; in the northern margin of the SWW belt) and Saunders et al. (2018), who report generally higher wind intensity after ~7 cal kyr BP at Macquarie Island (54°S; in the core of the SWW belt). The southward shift of the SWW belt would have allowed more influence from the high pressure belt in northern New Zealand, which is associated with lighter winds in general and clearer skies. Strong influence from the high-pressure belt is associated with a positive SAM at the present day, causing warmer and drier conditions in the Auckland region (Ummenhofer and England, 2007; Kidston et al., 2009), such as we find at Lake Pupuke in the mid-to-late Holocene.

Dry conditions in northern New Zealand during the mid-to-late Holocene also concur with increased ENSO activity and El Niño events reported after 5 kyr BP (Donders et al., 2005, 2007). In the South Island, Wilmschurst et al. (2002) and Jara et al. (2015) invoke increased ENSO activity during the mid-to-late Holocene to explain climate patterns, i.e. wet episodes at Eweburn Bog (southern South Island) and cooling at Adelaide Tarn (northern South Island) respectively. Although the climate shifts are different between the sites, they are consistent with an increasing El Niño influence, because these conditions cause reduced precipitation over the North Island and increased precipitation over the southwestern edge of the South Island, due to enhanced southwesterly airflow (Ummenhofer and England, 2007). However, we acknowledge that in invoking increased El Niño influence during the late Holocene, the modern ENSO spatiotemporal patterns have only been observed at much shorter timescales (decadal-to-interannual) than the long term, centennial-scale drying trend we find at Lake Pupuke.

Generally declining westerly wind strength in New Zealand (the northern margin of the SWW belt) and increasing El Niño frequency over the course of the Holocene are both consistent with findings of a southwards shifting intertropical convergence zone (ITCZ) during this period, causing a southward shift of the subtropical front (Haug et al., 2001; Putnam et al., 2012). Haug et al. (2001) postulate that this shift was caused by changes in the seasonality of insolation: Southern Hemisphere insolation is more seasonal during the late Holocene, while Northern Hemisphere insolation is less seasonal (Berger and Loutre, 1991, Fig. 5g). However, the observed wet period at Lake Pupuke (9.6–7.5 cal kyr BP) does not fully overlap with the period of lowest seasonality (~12.5–7.5 kyr BP). Other drivers may be at play here. Jara et al. (2017) found a similar PMI trend at Moanatuatua and argued that SWW were weaker in northern New Zealand between 12 and 8 cal kyr BP (see also McGlone et al. (2010a) on Campbell Island and Fletcher and Moreno's (2018) review of SWW reconstructions). The wet period at Moanatuatua (10–7 cal kyr BP) was attributed to an intensification of the subtropical circulation resembling the present-day La Niña state, bringing more subtropical moisture (Jara et al., 2017). However, Kidston et al. (2009) show that more northerly influence is associated with fewer cyclones and more anticyclones in most of the North Island, including the Auckland area. Additionally, as with arguments for stronger El Niño influence

after 5 kyr BP, there is an implicit assumption that the spatial patterns observed in modern ENSO cycles were played out over longer, centennial-millennial timescales during the early Holocene.

Whether the trends in effective precipitation at Lake Pupuke are related to atmospheric circulation (precipitation amount), SmT (evapotranspiration), or a combination of both, the apparent relationship between SmT and Southern Hemisphere summer insolation parameters is strong, as is their similarity to the PMI record after ~8 cal kyr BP. A further question remains as to whether this association reflects direct radiative forcing of local temperature or indirect forcing via regional-scale climate processes such as changing atmospheric or ocean circulation patterns.

6. Summary and conclusions

We reconstructed MAAT, SmT and effective precipitation over the last 16,000 years in northern New Zealand from the sediments of Lake Pupuke. SmT was inferred from chironomid assemblages, independent from MAAT and effective precipitation, which were reconstructed from pollen analysis. Pupuke MAAT increases coming out of the Last Glacial and stabilises after 10 cal kyr BP at close to modern values, consistent with nearby marine records of SST. There is no evidence for an early HTM. The vegetation changes that occur during the MAAT plateau are likely the result of changing humidity and seasonality. SmT increases between 10 and 3 cal kyr BP, in correspondence with local summer insolation parameters. Our results highlight the importance of undertaking future work aimed at expanding the chironomid training set with data from northern New Zealand sites.

Early-Holocene low seasonality (12–9.3 cal kyr BP) is indicated by cool summers reconstructed from the chironomid assemblages and mild winters inferred from the vegetation community and was likely driven by low local summer insolation intensity or summer duration. An early-to-mid-Holocene wet period (9.6–7.5 cal kyr BP) corresponds to relatively high westerly strength, consistent with a steep latitudinal insolation gradient. Mid-to-late-Holocene summers following the wet period were hot and dry (especially 4.0–2.4 cal kyr BP), allowing kauri to expand throughout northern New Zealand. High SmT would have increased evapotranspiration and decreased effective precipitation at the time. Whether low effective precipitation was primarily caused by increased evapotranspiration, southward displaced SWW, increased El Niño frequency, or some combination of these factors remains unclear. However, a strong correspondence is observed between SmT, Southern Hemisphere summer insolation parameters and PMI after 8 cal kyr BP.

The interpretation of our integrated MAAT, SmT and effective precipitation record leads to two main conclusions. Firstly, stable MAAT and increasing SmT at Lake Pupuke are consistent with increasing local summer insolation intensity and total summer energy during the course of the Holocene, mirroring the pattern observed in the Northern Hemisphere: there is no evidence for an early or mid-Holocene HTM, but rather, an early Holocene with cool summers and mild winters. Therefore, the early-to-mid Holocene does not appear to be a good analogue for future projected global warming impacts in northern New Zealand. Secondly, although MAATs were stable, vegetation at Lake Pupuke responded to changing seasonality and effective precipitation, highlighting the importance of multiproxy studies in addressing the complexities of climate patterns superimposed on MAAT reconstructions. Where Marcott et al. (2013) could not rule out seasonal and precipitation bias (cf. Liu et al., 2014), we actively searched for the influence of these factors on our proxies (cf. Sikes et al., 2013), leading to a better understanding of Holocene climate change complexities. While global compilations of temperature observations and global

climate model simulations may be useful for the mitigation of future climate change, they may not be representative of a particular region and may overlook important aspects of Earth's climate system.

Acknowledgements

We thank Jane Chewings for support with microfossil lab procedures, Xun Li for providing a pollen preparation protocol, James Renwick for insightful discussion of climate modes relevant to New Zealand's past and present, Matt McGlone for providing helpful comments on an earlier version of our discussion, and two anonymous reviewers for their constructive criticism. Postgraduate study of VB is funded through Marsden Fund project 14-UOA-040.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2018.10.008>.

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